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LASER BASED, NON-INTRUSIVE MEASUREMENT SYSTEM FOR ANALYSIS OF JET ENGINE FLOWS

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This document summarizes an effort to establish the feasibility of a technique which will allow the remote determination of the local flow velocity, temperature and density of selected species present in the combustion and exhaust flows of hydrocarbon fueled scram jet engine test facilities. We have developed a data acquisition system which is capable of high speed date collection (several kHZ) for time periods of many seconds before pausing for data transfer. In this program ~~we have~~ demonstrated a system prototype with a 16 millisecond capacity on a high speed combustor flow at Stanford University and ~~have~~ demonstrated that the local flow speed, temperature, and density can be recovered from the data. We use this data to estimate the potential signal levels which might be attained on the test facilities at WRDC and discuss how this approach might be configured and optimized on the quartz-walled test flow being developed there.

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PROJECT SUMMARY

This document summarizes an effort to establish the feasibility of a technique which will allow the remote determination of the local flow velocity, temperature and density of selected species present in the combustion and exhaust flows of hydrocarbon fueled scram jet engine test facilities. We have developed a data acquisition system which is capable of high speed data collection (several kHz) for time periods of many seconds before pausing for data transfer. In this program we have demonstrated a system prototype with a 16 millisecond capacity on a high speed combustor flow at Stanford University and have demonstrated that the local flow speed, temperature, and density can be recovered from the data. We use this data to estimate the potential signal levels which might be attained on the test facilities at Wright Laboratory and discuss how this approach might be developed for the quartz-walled test flow being developed there.

I. INTRODUCTION

This report is structured in three sections. The first describes the general features of SCRAM-Jet testing which necessitate new diagnostics, and how our proposed technical approach addresses these needs. This section discusses what information is needed to more fully characterize super- and hypersonic exhaust flows, and details the work plan taken in this Phase I study. The second section presents the results of the experimental work. This section also discusses the features which will be most important in the development of a prototype laser sensor system to probe these flows to obtain quantitative information. The final section develops the approach we propose for the Phase II program, discusses the sensor layout we will use in Phase II, and offers estimates of the measurement precision which are expected.

Background

Efforts are presently underway to develop new power-plants for high speed, air breathing aircraft. One area of particular interest is the development of supersonic-combustor RAM-jet engines, or SCRAM-Jets. These are under investigation by both NASA and Air Force in designs fueled by hydrogen or by hydrocarbons. The testing and development of such power systems on the ground is much more difficult than the testing of lower thrust systems because it is much more difficult to simulate the actual flight conditions. A SCRAM-Jet test stand must inject the front end of the system with hot, high speed gas. Typically this gas is pre-heated in a combustor located upstream and oxygen replenished by addition prior to the final SCRAM stage to simulate a natural air mixture. It is necessary to verify that this artificial mixture represents an accurate reflection of reality (i.e. that the gas is completely mixed and thermally equilibrated). Combustion kinetics are also very important at these high flow speeds (Mach 2-5) since poor mixing can result in slow burning and lost thrust and fuel efficiency.

Optical diagnostics can be useful in characterizing various media which are difficult to analyze using physical contact probes. Examples of such media are high speed gas flows and high temperature combustion processes. Both of these conditions are commonly encountered in the study of advanced jet engines. In particular, for SCRAM-jet inlet, combustion area, and exhaust flow analysis, such techniques are required so as to avoid serious disturbance of the flow itself. Several physical conditions of the flow can be of interest in designing a remote measurement scheme. The most important of these are velocity, temperature, and density.

In the past 20 years the technique of Laser Doppler Velocimetry (LDV) has become accepted as a means of determining flow velocities in wind tunnels and engine exhaust flows. In this approach small particles are seeded into the flow medium, which scatter laser light which irradiates the flow. The scattered light is Doppler shifted, and the magnitude of this shift is measured to determine the flow velocity at various points in the flow. This technique works well as long as the flow velocity is below $\sim$ Mach 1.5. Above these speeds the seeded particles cannot follow sharp vortices in the flow, and the desired flow field mapping detail is reduced. The quantitative analysis of such high speed (as well as high enthalpy) flows will require the development and proving of optical probes which interact directly with the molecular constituents of the flow itself. Techniques which interrogate the molecular constituents of a flow can be broadly characterized into four classes; fluorescence, absorption, light scattering, and transient grating schemes.

Transient gratings can be formed in liquids and gases through the spatial interference of two or more laser beams which are frequency tuned to optically excite a major constituent of the medium. The interference of the optical beams gives rise to a periodic pattern (or grating) with high and low optical intensity. This selectively excites the targeted flow species in the high field regions, forming an identical pattern of optically excited molecules. The movement of this pattern can be detected either by looking at the fluorescence waves move by a tightly focused photodetector, or by sensing the refraction of a third laser beam off of the grating pattern. While such techniques have been demonstrated in laboratory settings for the determination of flow velocity [1], the complexity of the required apparatus and the need for a strongly absorbing target species make them unattractive for application on engine test stands.

There are several approaches based upon light scattering, ranging from simple Rayleigh scattering off of the flowing gas constituents to the more sophisticated coherent anti-Stokes Raman spectroscopy (CARS) techniques. Rayleigh scattering results from the interaction of light with a molecule's electrons and is a non-resonant process. The magnitude of such scattering is proportional (for a given molecule) to the density of the medium and the intensity of the incident light. There is also a strong dependence upon the wavelength of the light used, which favors shorter wavelengths. The scattered light could be used to determine flow speeds (through Doppler shifts) as well as local flow density (from the signal magnitude). While such a simple process is attractive, the cross section (probability) for this type of scattering is very small and such signals are difficult to measure. Raman scattering occurs with a similar probability and results in scattered light with discrete changes in energy, although the process is also non-resonant. The energy changes are related to differences in rotational, vibrational, and electronic energy levels of the molecular constituents of the flow. Unfortunately, the signal levels are too weak to be of use in the analysis of hot flows.

Coherent anti-Stokes raman spectroscopy represents a special case of scattering in which several laser frequencies are employed to generate a directionally defined scattered light beam. This technique has been examined for applications in combustion remote sensing and flow analysis at Wright Patterson Air Force Base [2,3], by United Technologies Research Center [4], by NASA [5], and others [6-8]. While there is some difficulty in quantifying the observed line intensities, the approach can be quite powerful. The biggest problem with CARS is that the scattered beam is generated at a small angle to the incident beams, and so a clear line of sight passage through the flow must be used to recover the signal. This is not possible in many applications.

Optical absorption and fluorescence techniques have been under development for a much longer time and offer greater potential for widespread application. A number of approaches based upon laser induced fluorescence (LIF) have recently been reviewed [9]. Laser based fluorescence measurements can be either point measurements [10-12] or two dimensional images recorded on array detectors [13-16]. In applications with high concentrations of the target molecule to be laser excited, signal levels can be high enough to make 2-d images of flow parameters. In systems where the signal-to-noise levels are more modest, the point measurements are preferred.

We propose to develop a new technique which will measure flow speed and temperature with good precision, as well as a less precise determination of local flow density (see below). The approach offers good temporal and spatial resolution and can be used to make both point and line of sight integrated measurements simultaneously. These measurements can be made at kilo-Hertz data accumulation rates. The technique is based upon the measurement of a Doppler shifted laser induced fluorescence (LIF) signal of a flow constituent, the OH radical. While other LIF based velocimeters must average over many seconds to record a Doppler shift, the significant innovation in this approach is the application of a new technique which permits the rapid frequency modulation (kHz) of a single mode dye laser. The approach described in this report offers a thousand-fold increase in the time resolution attainable by such systems. Integration of this technology into a laser-Doppler velocimeter will permit non-intrusive determination of flow speeds ranging from sub-sonic to speeds in excess of Mach 10 with an estimated accuracy of +/- 50 m/sec for the flow speed. At the same time the system can also determine the local temperature over the range $400 < T < 3400$ K with less than $\sim 5\%$ error for unaveraged, single cycles of the laser modulation. Local density can be determined from the collisional broadening observed for an absorption line of the radical with an estimated accuracy of +/- 20% for point measurements. Incorporation of an integrated absorption measurement can provide line of sight (LOS) integrated measurements of flow velocity, temperature, and density, with significantly better accuracies. For example, the LOS integrated density measurement has an estimated uncertainty of only a few percent. These LOS measurements can be used to provide total weighted mass flux measurements, which would be useful in the determination of engine thrust.

SUMMARY OF SYSTEM PERFORMANCE*

I. TIME RESOLVED POINT MEASUREMENTS

Time resolution	$\sim 3\times10^{-4}$ sec.
Flow velocity range	above 50 m/sec
Flow velocity resolution (for a single system cycle)	$\sim$50 m/sec
Flow temperature resolution (for a single system cycle)	$\sim$5%
Flow local pressure precision	+/- 20%

II. TIME RESOLVED L.O.S. MEASUREMENTS**

Time resolution	$\sim 3\times10^{-4}$ sec.
Flow velocity range	above 50 m/sec
Flow velocity resolution (for a single system cycle)	$\sim$20 m/sec
Flow temperature resolution (for a single system cycle)	$\sim$2%
Flow pressure (mass wieghted)	2-3%

* Based upon data produced in this study

** Line Of Sight integrated measurements

GOALS OF PHASE I PROGRAM

The most direct means by which the speed of a moving medium may be remotely determined is through the Doppler shift imparted to the frequency of any light scattered off of the medium. Direct optical probes of high speed flow velocity based upon the measurement of Doppler shifted scattered light are possible, but extremely difficult. Any optical technique which uses scattered light as a probe of the flow medium velocity must ultimately determine the magnitude of the Doppler shift produced. A scattering scheme based upon atomic or molecular absorption/fluorescence must further deal with a natural line width which is comparable to the Doppler shift produced by a Mach 1 flow (at or near combustion temperatures), which for laser wavelengths in the visible is typically $\sim 0.1\ cm^{-1}$ for temperatures near 1000 K.

Under ideal conditions, such spectrally resolved measurements can be made using either interferometric or wavelength dispersive techniques. The anticipated signal levels in actual test cells or laboratory simulation are too low to permit measurement by interferometric techniques. The required sensitivity and resolution are at the performance limits of practical dispersive optical instruments (monochrometers) even in a laboratory setting. Significant technical problems must be overcome before vibration sensitive instruments, such as monochrometers, can be located within a test cell environment.

These problems can be overcome by encoding all of the frequency information in a laser excitation source. In such an approach a narrow band continuous laser would be frequency scanned through an optical absorption resonance of a selected constituent of the flow. When the laser is in frequency resonance, the excited species radiate fluorescence which can be detected by a photomultiplier. The flow speed is determined from the measured Doppler shift, which is the difference between the observed excitation resonance frequency and that of a sample at rest. While such a scheme has been demonstrated, the rate at which data could be attained is low because narrow band or single mode dye lasers are difficult to modulate quickly over the required frequency range ($+/- \sim 0.5\ cm^{-1}$). This means that the Doppler (flow velocity) information is averaged over a time period of $\sim$20 seconds. While this is sufficient for measurements of stable flows alternative approaches must be developed to provide adequate mapping of turbulent flows with variations greater than 0.05 Hz.

Recently, a technique which permits the rapid frequency modulation of a cw single mode laser has been developed and demonstrated [17,18]. The technique makes use of a pair of optical prisms located within the laser cavity in such a fashion that a change in prism angle results in a small change in the cavity length (and the stable cavity frequency mode) while maintaining single mode operation. Rapid modulation of the prism angle results in a modulation of the output frequency. This technique has been used to rapidly scan over several ro-vibronic components of the OH radical in a flame (by frequency doubling the modulated laser output) from which a temperature was determined.

By scanning the laser frequency over a flow constituent absorption line, a laser induced fluorescence signal can be stimulated. We have developed a sensor system based upon such a laser system and have used it to record time resolved point measurements of flow velocities, temperatures, and densities in a supersonic combustion flow. This approach has already been demonstrated as a means of determining time averaged velocity, density and temperature in a hot flow. We have developed a system which provides a kHz data rate determination of these parameters. We have carried out this work in collaboration with Professor R. Hanson of Stanford University. This collaboration has provided us with the technical expertise of the laboratory which developed the proposed optical technique as well as the hardware required for a Phase I demonstration. The availability of these facilities and associated expertise offers the proposed SBIR Phase II program a significant savings in development time and money. The goals of the Phase I effort were:

1) Select a species expected to be abundant in the SCRAM-Jet exhaust;

2) Select a spectroscopic approach;

3) Configure the data collection hardware and software;

4) Make preliminary measurements;

5) Evaluate data and make estimates of performance and sensitivity;

6) Develop Phase II objectives.

SPECIES SELECTION

Species which might be present in SCRAM-Jet exhausts include:

OH the hydroxyl radical; this species can be optically accessed through the $A^2\Sigma$ - $X^2\Pi$ electronic transition which has a (0,0) band near 308 nm.

NO Nitric oxide can be produced in the combustion process or can be added to the flow; this species can be optically accessed through the $A^2\Sigma$ - $X^2\Pi$ electronic transition which has a (0,0,) band near 227 nm.

M other impurities, such as metal atoms, etc.

Selected species could be seeded into the flow to act as a target for the laser excitation, however we seek a more general probe of the combustion flow. This limits the practical choice to either OH or NO. While both of these species would be present in high temperature combustion flows (T>3000 K), the concentration of NO falls off rapidly for temperatures below this level. This species is also much more difficult to target using a continuous, frequency doubled dye laser because the required wavelength (227 nm) is difficult to generate. The OH radical offers several advantages which support it's selection as the target species. The strong A-X electronic transition occurs at a wavelength which is ideal for the operation of this laser system. The radiative lifetime and chemical kinetics of this species (in both electronic states) are well characterized, and it is expected to be present in the SCRAM-Jet exhaust flows at 0.1 - 0.01 % levels. Our experience with this species leads us to select it as the target for this laser excitation scheme. Once the prototype sensor, based upon the OH radical, has been developed it could be modified later to operate based upon LIF of NO using essentially all of the same equipment.

The sensor system we propose to develop will measure several hot flow parameters. These are flow velocity, flow temperature, and local flow pressure. These quantities allow the user to determine several other important quantities, such as engine thrust, fuel mixing, and turbulence. The basis for the measurements we propose to make are the following:

velocity: measure the frequency shift between the flow LIF signal and that from a static reference sample

temperature: measure the LIF signals from two rotational components and use relative populations to determine T

pressure: fit the observed LIF peak shape to a Doppler/pressure broadened curve to deduce pressure

The approach we propose to take in the determination of flow velocity has already been discussed. The basis of the temperature measurement is the determination of the relative populations of two rotational levels of the OH radical. We have selected the $R_1(7)$ and $R_1(11)$ line pair because this pair can be used over a wide range of temperatures with good accuracy. The relative line strengths for these lines are plotted as solid lines in Figure 1 for the temperature range 0 - 5000 K. This plot demonstrates that the intensities of the two lines differ significantly below 3000 K and that their ratio is sensitive to temperature over the range from ~400 - 3300 K. The dashed line refers to the ratio of the $R_1(11)/R_1(7)$ line strengths and is referenced to the scale on the right side of the figure. This ratio plot demonstrates a good temperature variation.

Temperature is determined from the ratio of the R(11) to R(7) lines. The fluorescence line strength is proportional to the population in each rotational level. To a first approximation (assuming no electronic state degeneracy) this is given by the Boltzmann distribution.

$$\text{Pop.} \sim (2J+1) \times \exp[-BJ(J+1) \times hc/kT]$$

taking the ratio between R(11) and R(7);

$$\text{Pop.}[R(11)/R(7)] \sim \text{Const.} \times \exp[-1900/T]$$

A more accurate analysis must consider the electronic state degeneracy of the OH radical resulting from both electronic spin, and orbital angular momentum effects. The correct expression for the intensity of an electronic transition would replace the pre-exponential factor (2J+1) with the proper **Honl-London** factor. While this modification of the analysis alters the calculated line intensity, it does not effect the **temperature** dependence expected for the ratio of a pair of lines.

For intensity fluctuations giving a ratio error of a few %, the corresponding error in temperature would be a few %. The preliminary data we will present in the next section indicates a probable temperature error of ~4% - 5%.

II. TECHNICAL APPROACH

The key to making a Doppler shift determination of a flow velocity is determining the line center of the Doppler shifted fluorescence signal. In our approach the frequency precision is provided by a narrowband continuous dye laser which is frequency modulated over a small range (near a molecular absorption). The dye laser bandwidth (MHz) is much smaller than

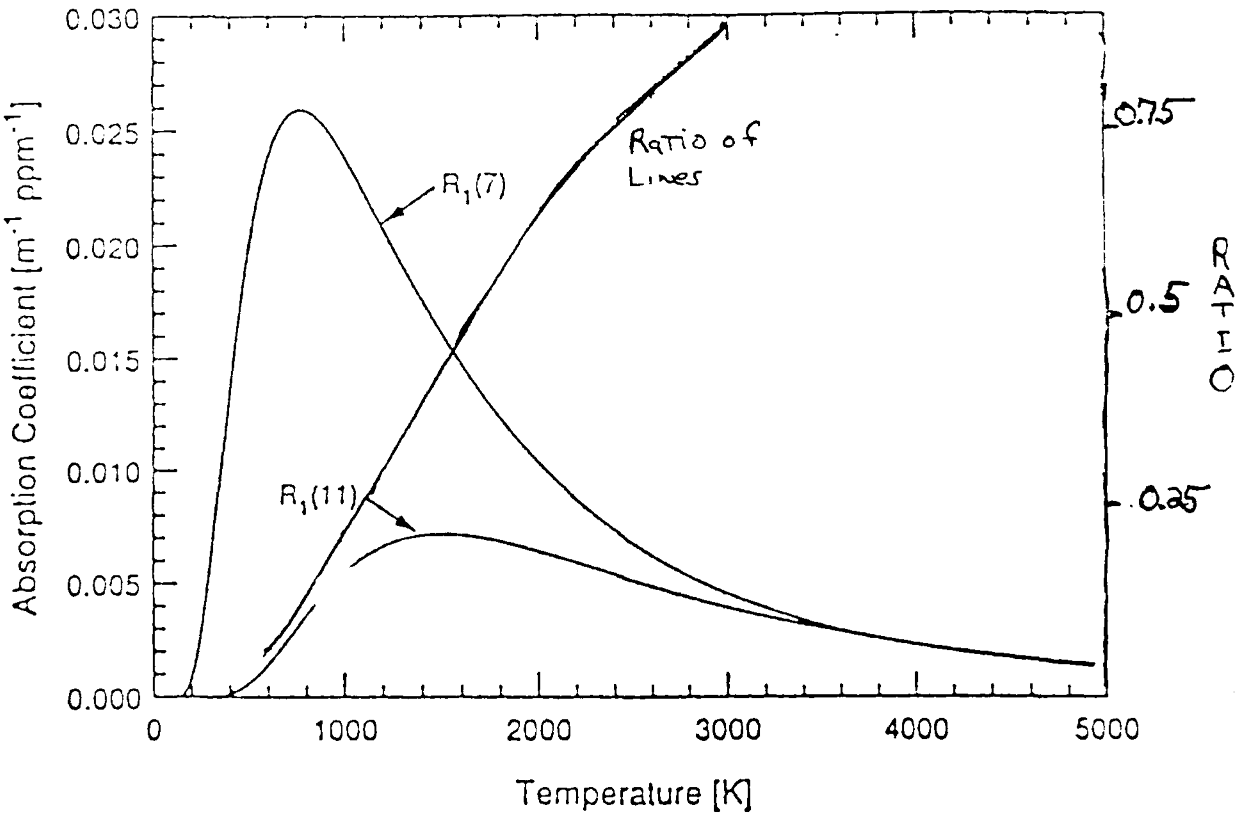

FIGURE 1 Temperature dependence of the line center absorption coefficients of the R(7) and R(11) lines in the OH $A^2\Sigma$ - $X^2\Pi$ (0,0) band transition

that of the molecular absorption (GHz) and can be treated as a delta function. The laser frequency would be modulated over a 0.5 cm^{-1} range and so can measure Doppler shifts corresponding to flow speeds of $\sim 4 \times 10^5$ cm sec^{-1} ($\sim$twelve times the speed of sound at STP). The key to the approach is in recognizing that the precise frequency of the dye laser is a function of the phase angle of modulation, and so a given Doppler shifted excitation will occur at a fixed time in the modulation cycle. In effect, by precise control of the laser frequency, the measurement of a Doppler shift is reduced to that of a time delay.

The frequency modulation technique to be used is based upon the work of W.D. Phillips [17]. He made use of the fact that cw ring dye lasers can be made to oscillate on a single axial mode using relatively weak intracavity selection. This behavior is apparently caused by the strongly homogeneous nature of the gain saturation mechanisms in organic dye gain media, and the unidirectional ring cavity design which eliminates mode coupling through spatial hole burning. Using only a single intracavity thin etalon with a free spectral range of 450 GHz, and by varying the effective cavity length by angle tuning a Brewster plate, he realized rapid scans over a spectral range of $\sim$8 GHz while retaining stable, single mode output.

The frequency modulation technique has been developed for operation in the UV and demonstrated at kHz cycle rates [18,19] and for spectral ranges of greater than 30 GHz (1 cm^{-1}). The cw ring dye laser, operating on a single cavity mode, is modified by inserting two rhomb elements into the cavity optical path. The angle of both rhomb elements is modulated, providing a controlled modulation of the effective cavity size. This modulation in the cavity size results in a modulation of the single mode frequency output. The use of two rhombs compensates for the slight displacement of the beam introduced by passage through the rhomb element, and makes it possible to retain fixed cavity mirror settings. This technique has recently been used to scan over several molecular absorption lines in a combustion environment, providing temperature determinations at 3 kHz data rates [18]. The frequency modulated UV light is coupled out of the laser and directed to the fast flow to be probed. Two small window reflections are sampled and digitized in parallel to the LIF signal from the flow. One of these is simply a measurement of the laser power, which smoothly oscillates by $\sim$10% with the frequency oscillation. The second signal is an OH absorption signal produced by passing the reflection through a stationary flame. This signal provides a frequency reference for the OH LIF lines since the OH in the reference flame is not moving relative to laser beam axis. The sample LIF spectra and the reference absorption signals are then normalized for the laser power oscillations. A portion of the dye laser fundamental light is also sampled and passed through an etalon into a silicon detector to provide frequency markers for later determination of the OH Doppler shifts. Because the laser frequency is sinusoidal, the markers are unevenly spaced. The OH fluorescence was collected by a filtered PMT (Hamamatsu 1P28) and the resulting signal digitized. A schematic representation of the hardware setup is shown in Figure 2.

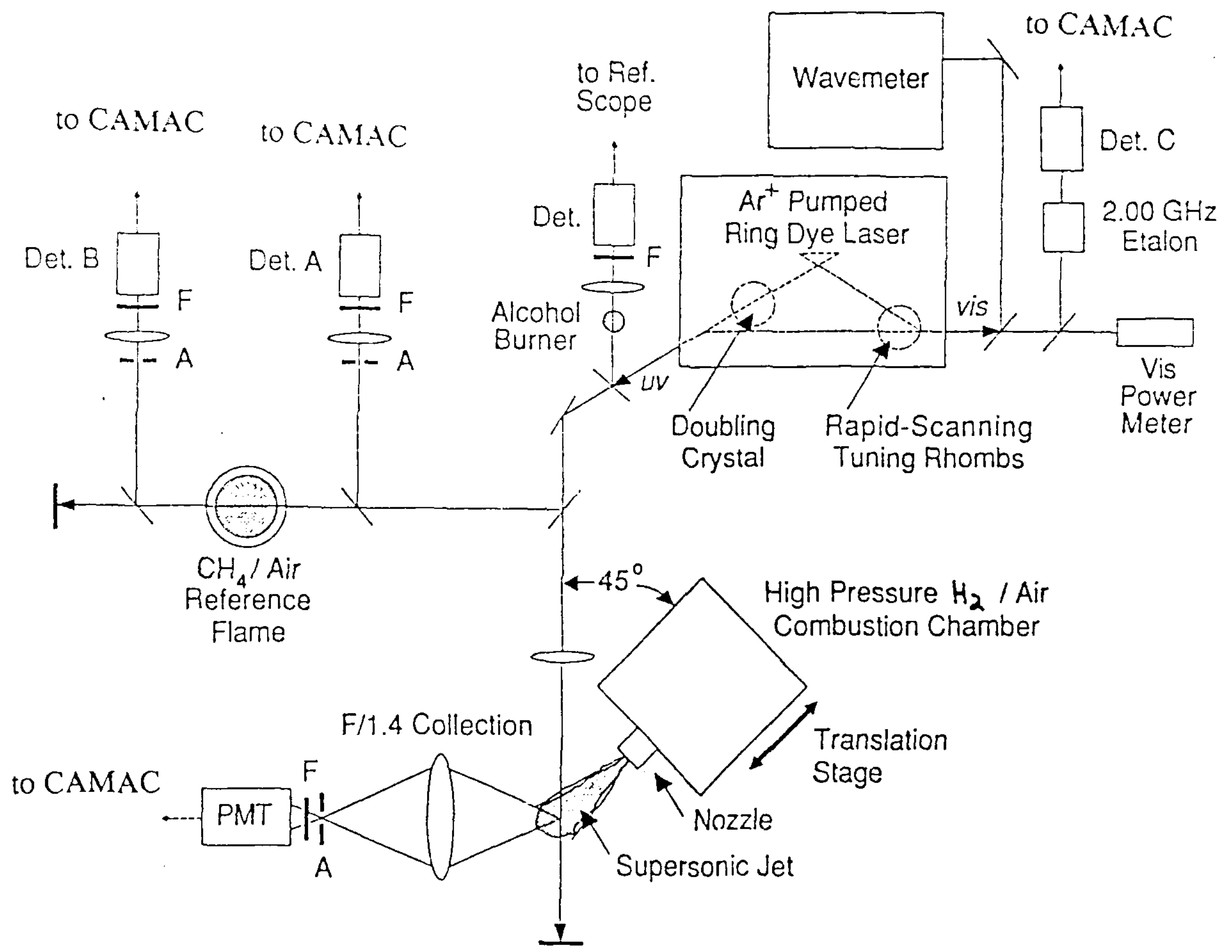

FIGURE 2 Schematic representation of the sensor layout used in the Phase I study

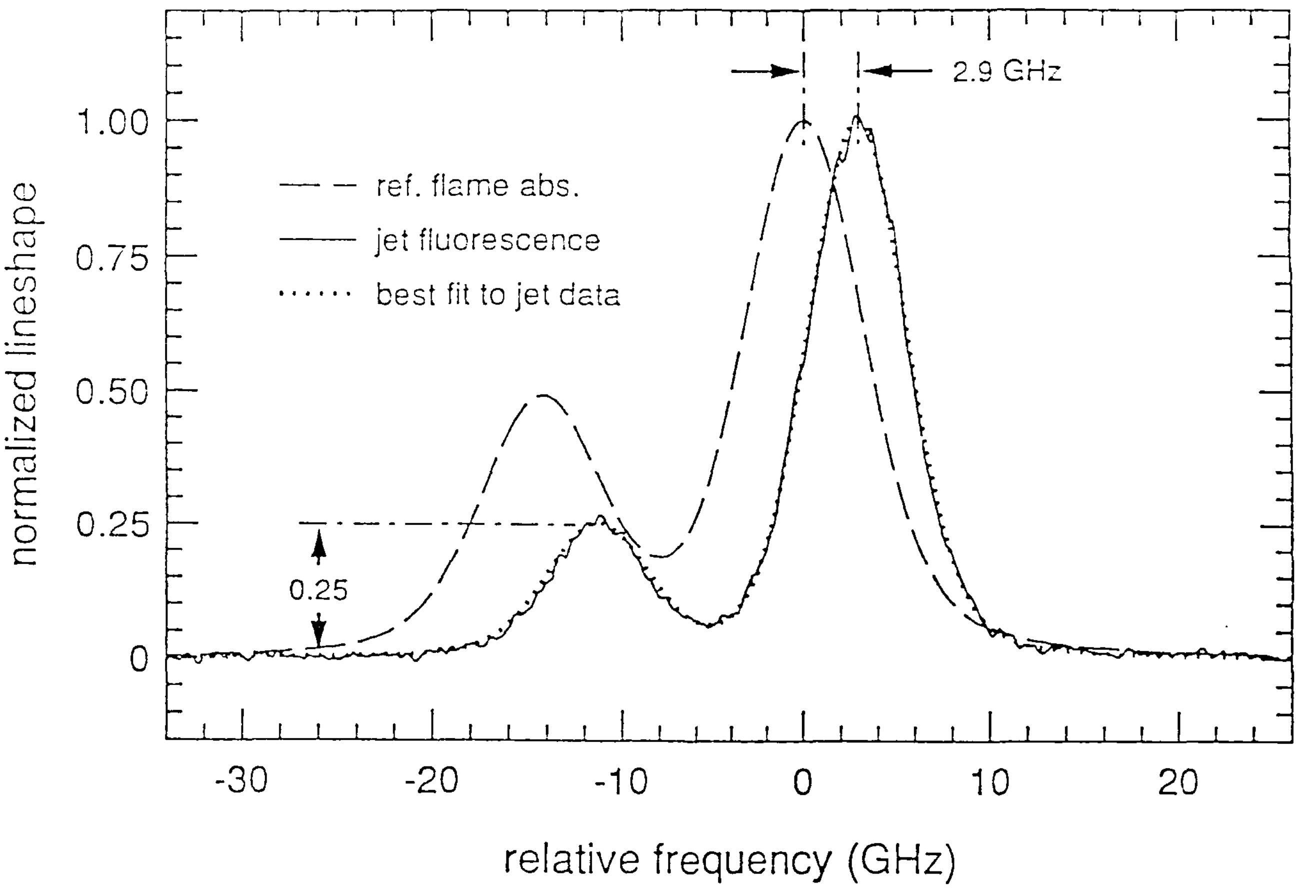

FIGURE 3 Typical data from Hanson, et al. [19] showing reduced data signals. Velocity resolution is ~0.1 GHz, or +/- 50 m/sec.

A representative spectrum indicating the frequency shift relative to a reference (unshifted) spectrum is shown in Figure 3. The data shown in Figure 3 (taken from Ref. 19) represent the LIF signal from the R(11) and R(7) lines as the laser frequency is swept, and is the average of several laser sweep cycles. This data was collected using the same laser and supersonic jet burner as used in this Phase I study, and is representative of the quality of data which can be attained. Several features should be noted. The signals (both LIF and reference absorption) have been normalized for the laser power variation. The x-axis has been converted from time to laser frequency using the etalon markers. The Doppler shift seen for the LIF signal in Figure 3 is indicated for the R(7) line, $\Delta\nu = 2.9$ GHz. Our measurements indicate that the shift can be measured directly from such a figure with an estimated uncertainty of $\sim$0.1 GHz. The precision which results from fitting the LIF peaks to a Voigt profile is even better. This corresponds to a velocity resolution of $\sim$50 m/sec.

The inferred velocity is a linear function of the frequency shift with a proportionality constant of 306.5 m/sec per GHz shift. The 2.9 GHz shift seen in Figure 3 corresponds to a velocity of 890 m/sec along the laser beam. Since the laser beam intersected the flow at an angle of 45 degrees, the inferred centerline velocity is 1260 m/sec. The estimated error in determining the center frequency of the Doppler shifted signals is $\sim$0.3 GHz (90m/sec) for non-averaged, single cycle spectra. This error can be reduced by selected averaging.

The ratio of the two peak heights, R(11)/R(7), is used to determine the local temperature. This determination is based upon the equilibration of the rotational levels of the radical with the flow gas and, as discussed above, is a simple function of the rotational level and the rotational constant of the radical. The relative populations of the two different rotational levels can be determined by two different means. One approach is to directly measure the relative peak heights of the two lines [20]. The second approach is to fit the entire profile to determine the area under the curves, and thus, the intensity ratio. The first approach is much faster than the second, although the second should, in principle, be more precise. Using the data shown in Figure 3, temperatures of 1070 K and 1080 K were calculated using the peak height and peak fitting approaches respectively. This good agreement suggests that the faster peak height approach should be sufficient for the work proposed here.

OH RADICAL DETAILS

As a result of the energetic chemistry in the combustion region and the high temperatures which characterize exhaust flows, a significant density of OH radicals will be encountered. The exact concentration profile of OH in the flow will be a function of flow density and temperature, and is the subject of ongoing studies. We estimate that the OH density in the supersonic jet employed in this Phase I study was $\sim 10^{16}$ cm^{-3}. The optical absorption cross section, σ, for the OH (A-X) electronic transition at 3000 Å is about 10^{-17} cm^2 [21]. The resulting absorption coefficient, $k = C \times \sigma$, is $\sim 10^{-2}$ cm^{-1}. More precise estimates of the line center absorption coefficients can be made using the tables of Goldman and Gillis [22] in which relevant data is tabulated for high temperatures.

The spectral shape of a resolved rotational component can be modeled by a Voigt profile [23]. The Voigt function describing this lineshape is the convolution of the Gaussian profile resulting from the Doppler broadening with a Lorentzian profile resulting from collisional broadening. The overall spectral line width resulting from this convolution will be a function of temperature, and will generally be within the range $\sim$0.04-0.2 cm^{-1}. The collision free radiative lifetime of the upper electronic state in OH is short ($\sim$700 nsec) and so fluorescence is produced only when the exciting laser is in resonance. The effective lifetime is even shorter as a result of collisional quenching. This quenching is most efficient in OH collisions with water molecules, which will be abundant in the exhaust flow. The quenching rate at elevated temperatures ($\sim$1500 K) has been studied [24] and, for a H_2O density of $\sim 10^{18}$ cm^{-3}, is about 100 times faster than the radiation rate. This quenching reduces the number of photons emitted by this factor.

Data Collection System

One of the goals of the Phase I program was to demonstrate the operation of a compact and reasonably inexpensive data collection system. The approach we have taken is based upon a modular design which has the advantage of being easily expanded, both in the number of signals to be recorded and in the amount of data storage available. Our prototype system used four 8-bit, 100 MHz transient digitizers to record the four signals of interest, which were triggered simultaneously. The digitizers were mounted in a CAMAC crate which permits easy function expansion simply through the addition of additional digitizers. The crate was interfaced to, and controlled by a small computer (386 processor), which allowed for data storage, analysis, and viewing.

Experimental Results

The data which will be shown in this section consists of photos (or photocopies) of the data as displayed on the computer screen. The data is identified by a file name located near the center-top of each figure. This file name consists of a date, followed by a running number. The legend at the top of each figure also indicates the record length, or the number of time intervals digitized. It also indicates the time interval between these points. We typically operated using 1000 nsec time intervals for the maximum allowed 16384 samples. In this configuration the data represents a 16.384 msec picture of the flow which is probed at 3 kHz. Each data file contains 48 scans over the OH radical R(7)/R(11) line pair, as well as all of the supporting diagnostic signals. Since this results in a highly congested picture, the controller program permits the selection and expansion of time windows within the range of a data file.

A typical set of results is shown in Figure 4. This figure is made up of all four digitizer traces which are offset from each other for clarity. The x-axis represents time in units of nanoseconds, and runs from 0 to 16384000 nsec. (16.384 msec). In this figure the oscillating laser power and reference absorption traces are overlayed at the top, where the sharp decreases in signal indicate the absorption lines. Running along the center of the figure is the LIF signal from the OH in the jet. Each of the upward spikes is really made up of the two LIF lines, which are closely spaced and difficult to resolve on this scale. The trace at the bottom of the figure is the output of the diode which monitors the reference etalon transmission. Each spike in this trace represents a 4 GHz change in laser frequency. While the detail is difficult to resolve at this level of data compaction, it is clear that the OH LIF signal is varying greatly in intensity. This variation appears to be a smoothly varying phenomena rather than peak-to-peak noise. A section of data, from 12.288 msec to 16.384 msec, from the same data file is shown in Figure 5. Some of the finer details of the data are becoming noticeable at this magnification; the absorption line doublets are better resolved, as are those of the LIF trace. From the data shown in Figure 5 it is clear that the variation in OH LIF signal is not due to variation in the laser output power and must be the result of a variation in the density of the OH radical at the image point.

A greatly expanded segment of data from another file is presented in Figure 6. At this magnification all of the relevant features are clear. The signal to noise seen for the OH LIF trace (center) is about thirty-to-one for individual pairs of peaks. The order of appearance for the pair of peaks alternates because the laser frequency is varied over the pair during both legs of it's oscillation. The sinusoidal variation of the laser frequency is easily seen in the variation in spacing between the etalon transmission spikes. Finally, at this magnification it is possible to visually discern a slight frequency shift between the reference OH absorption trace at the top, and the OH LIF trace at the center. The width of each line is $\sim$6 GHz.

Another data file is shown in Figure 7. The oscillations in the OH LIF signal is again seen. The time scale for these oscillations is 3 - 6 msec, or a frequency of hundreds of Hertz. This data indicates that the combustion process is uneven and could suggest a problem with the gas mixing or burning. Additional work will be required to study this phenomenon and to determine it's significance. It is worth noting that if the target gas species had been something which had to be seeded into the flow, this non-uniformity would not have been seen. This points out one of the advantages of targeting the OH radical.

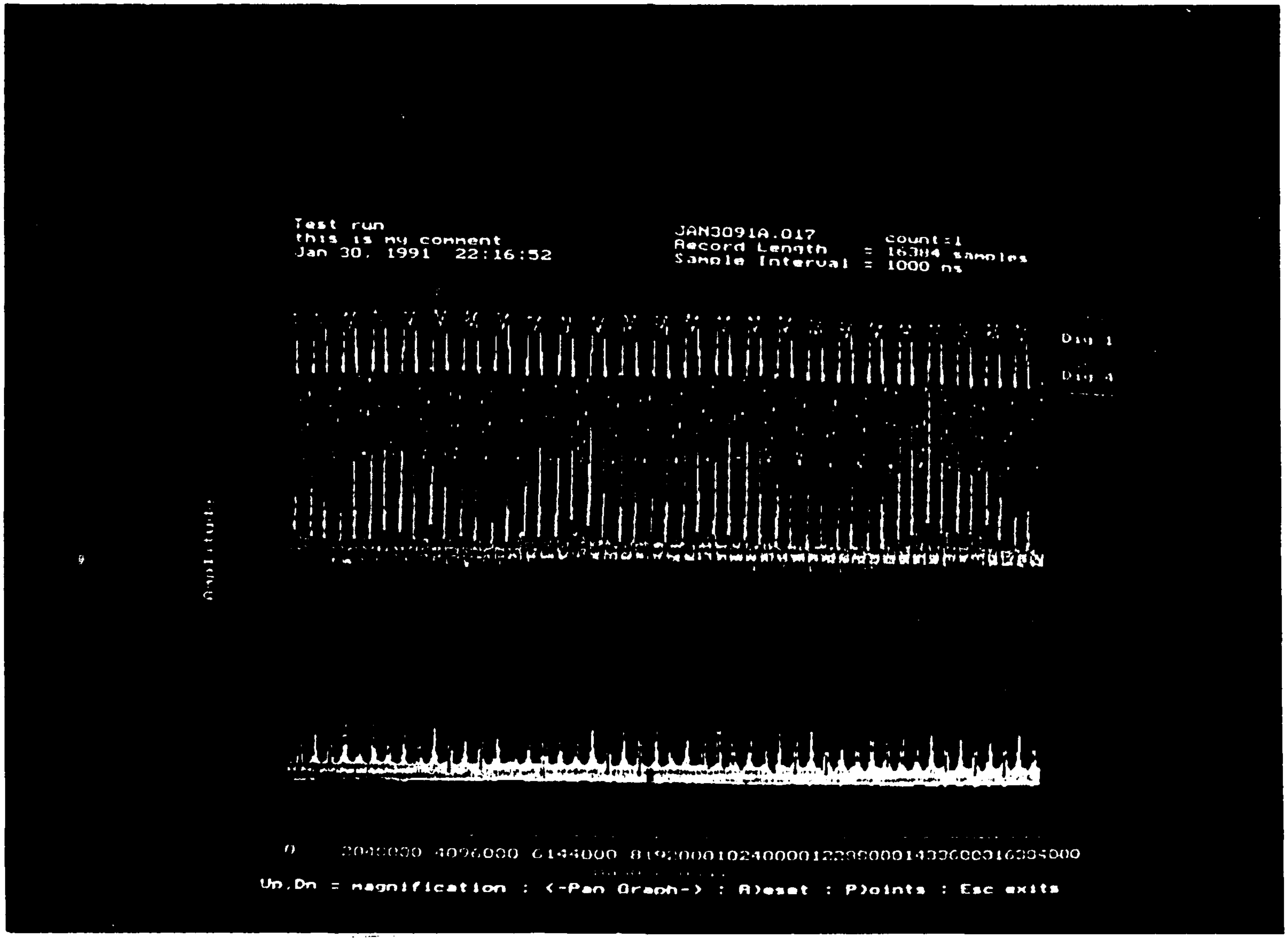

FIGURE 4 Typical data collected using our prototype system. The data traces are explained in the text.

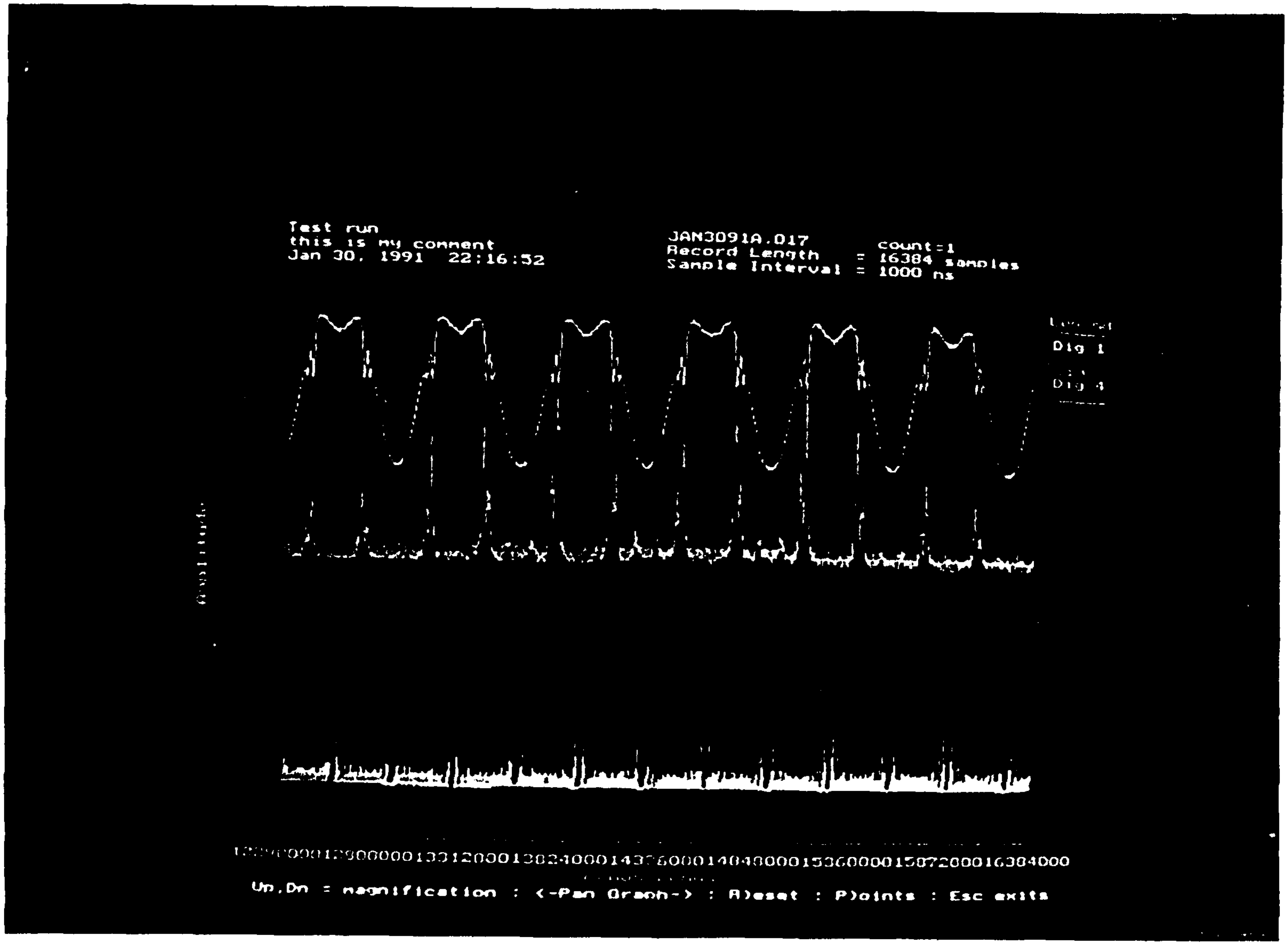

FIGURE 5 Magnified view of the data from 12.288 - 16.384 msec from the same data file as shown in Figure 4. Note the variation in the OH intensity.

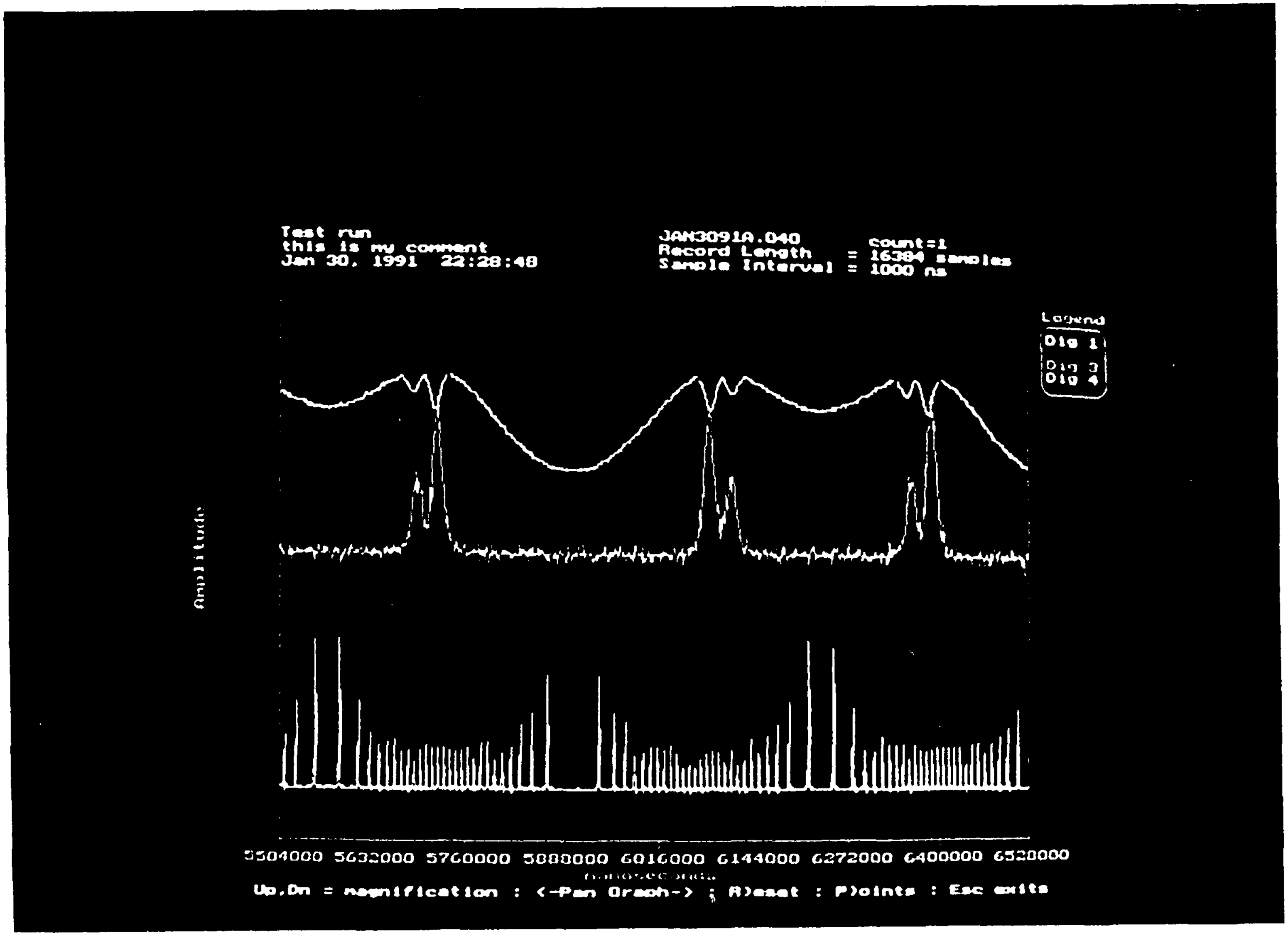

FIGURE 6 Magnified view of another data file. At this magnification all of the relevant features are clear.

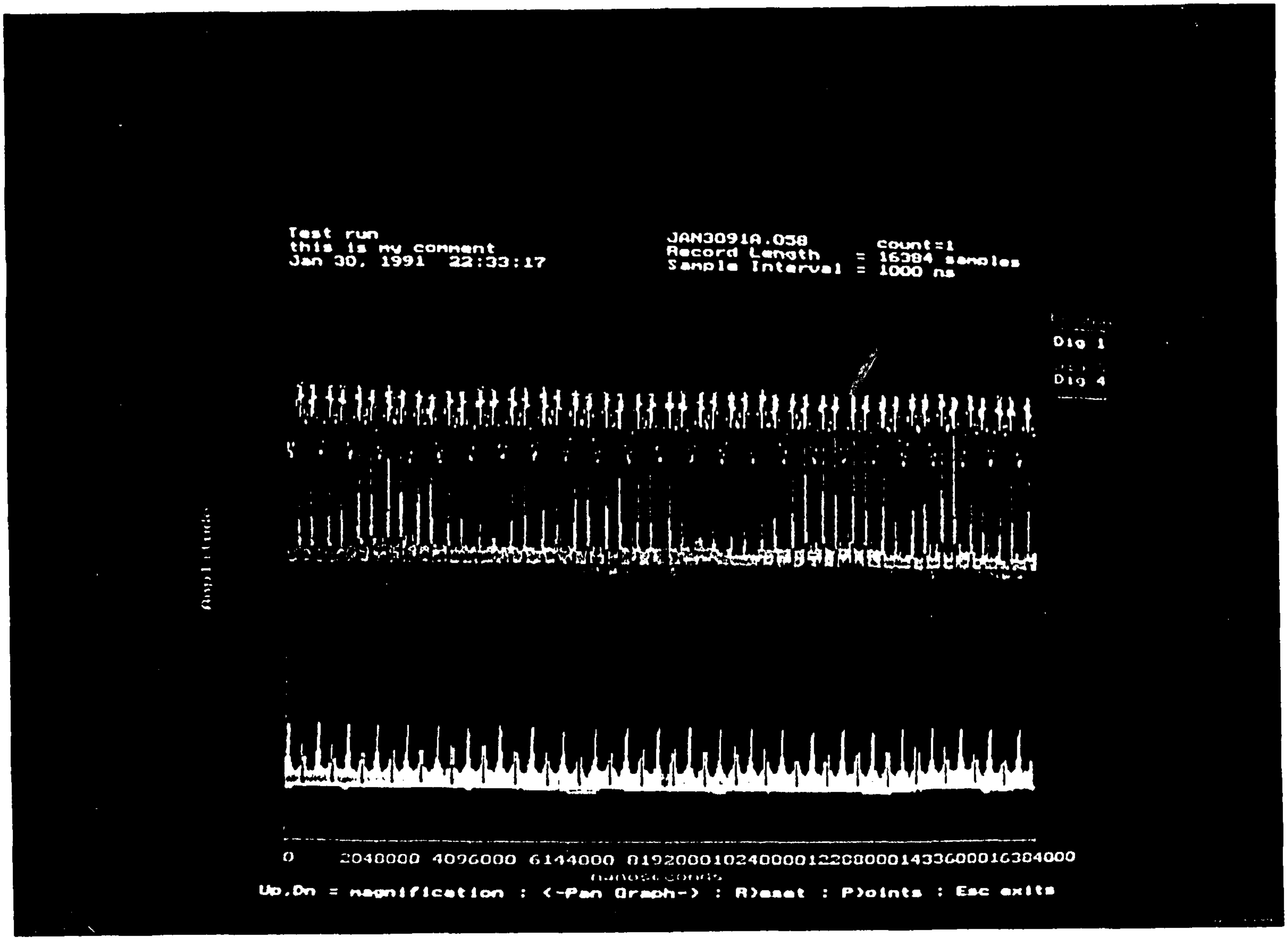

FIGURE 7 Another data file showing the OH oscillations observed using our approach.

Because these packets of OH seem to reflect spatially distinct waves of combustion product passing through the laser beam with time, it is possible that each wave or packet might reflect slightly different temperatures. Figures 8,9, and 10 show magnified views of the data for times 1.408-2.432 msec., 6.144-7.168 msec., and 11.080-12.032 msec. respectively. We have measured the relative peak heights for the R(11) and R(7) lines to estimate the temperature and list the ratios in Table I for each of the three line pairs in each time range.

TABLE I

Time Range	Line pair Ratios	Average Ratio	Average Temperature
1.408-2.432	0.51, 0.52, 0.406	0.479	1620 K
6.144-7.168	0.492, 0.521, 0.511	0.508	1650 K
11.08-12.032	0.505, 0.492, 0.500	0.499	1640 K

The temperatures can be calculated or simply estimated from the ratios using the curves given in Figure 1. This estimate demonstrates that the temperatures of the different packets of OH are very similar over the course of the $\sim$16 msec. window captured by our data system. This estimate also indicates the variation in measured quantities which might be expected when using individual line pairs to determine temperature. This variation is small. We have also estimated the temperatures of line pairs on the edge of the packets (weak lines) to determine if the decrease in OH concentration were due to lower temperatures. While it is much more difficult to make these estimates because the signal is very weak, the data suggest there is no significant difference in temperature. This clearly suggests that the bulk gas in the flow has come to local thermal equilibrium.

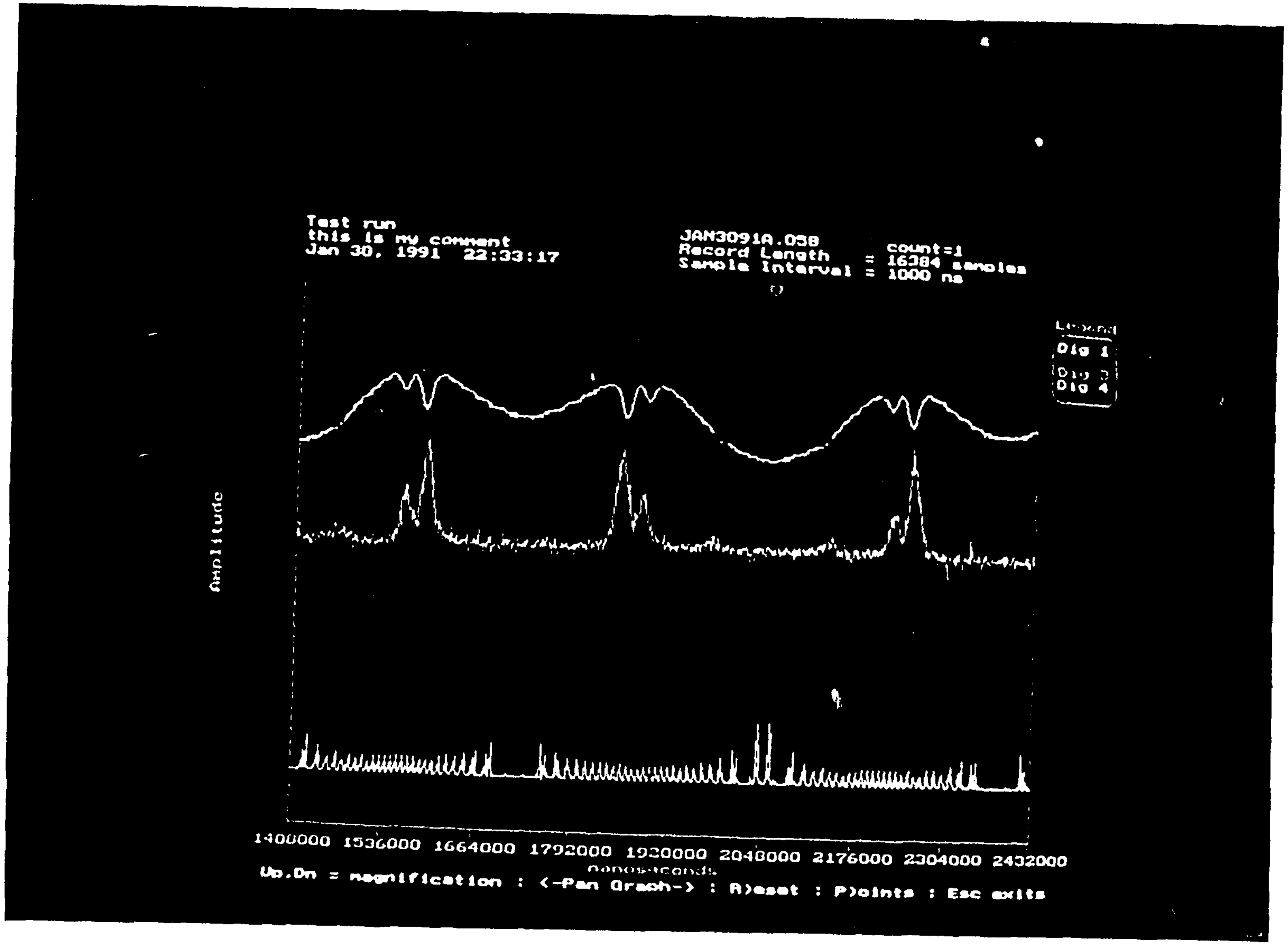

FIGURE 8 Magnified view of the data shown in Figure 7. This shows the range 1.408-2.432 msec.

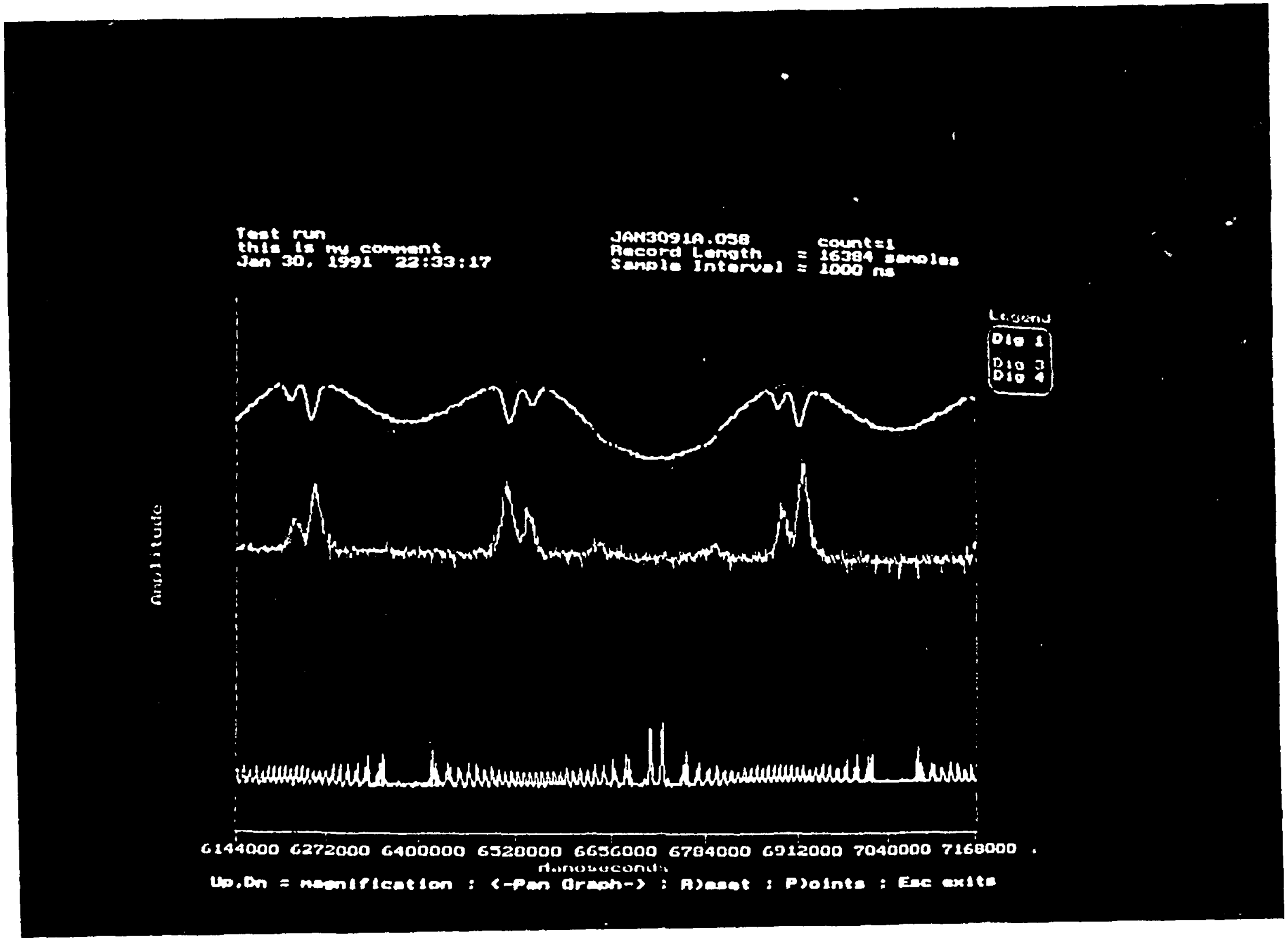

FIGURE 9 Magnified view of the data shown in Figure 7. This shows the range 6.144-7.168 msec.

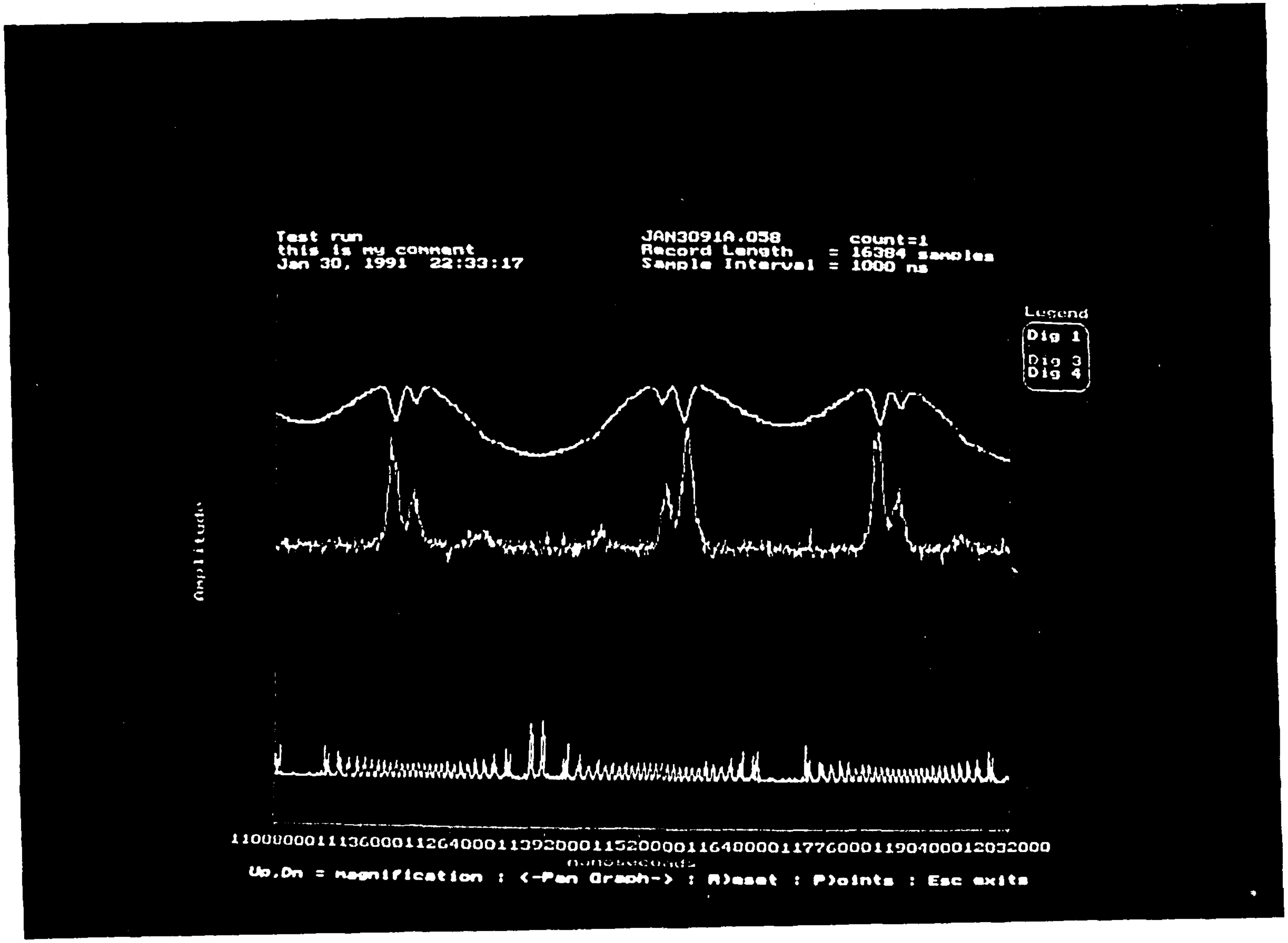

FIGURE 10 Magnified view of the data shown in Figure 7. This shows the range 11.08-12.032 msec.

CONCLUSION OF EXPERIMENTAL RESULTS

The experiments we carried out have demonstrated that rapid modulation of a dye laser frequency can be used to scan over several lines of the OH radical in a supersonic flow, and the resulting laser induced fluorescence used to determine local flow velocity and temperature. This technique has been developed by the group at Stanford with whom we are collaborating. One of the goals of the Phase I program was to develop and demonstrate the capability for collecting and handling large amounts of data obtained using this approach. The data system we have developed has this capability and can be greatly expanded.

We have observed, for the first time, significant temporal oscillations in a major combustion product, OH. These variations would be impossible to see using other probes based upon pulsed laser technology, such as CARS, 2-d imaging, etc.

SYSTEM EXTENSIONS

The LIF measurements described above represent point measurements and can be augmented using line-of-sight integrated absorption. This approach would make use of the same laser system and detection system, and would provide a mass weighted measurement of flow speed across an exhaust flow. These measurements would be carried out in parallel to the LIF detection, using the same laser beam. The basic configuration is shown in Figure 11. The resulting data would be similar in appearance to that shown in this report, and would be reduced in a similar way. The signal to noise is much better for such an absorption measurement and the resulting quantities will be of significantly greater precision. Typical velocity data is shown in Figure 12. Typical estimates of average temperature are presented in Figure 13.

The data system we used in Phase I was based upon four 8-bit, 100 MHz digitizers. We propose to base the Phase II data system on a new digitizer (LeCroy Model 6810) which has 12-bit resolution and can store up to 8 million data points. At the same data rate used in this work, such a system would have the capability to digitize and store 8 seconds of flow information. This represents a tremendous amount of information, and re-enforces the need for rapid data evaluation.

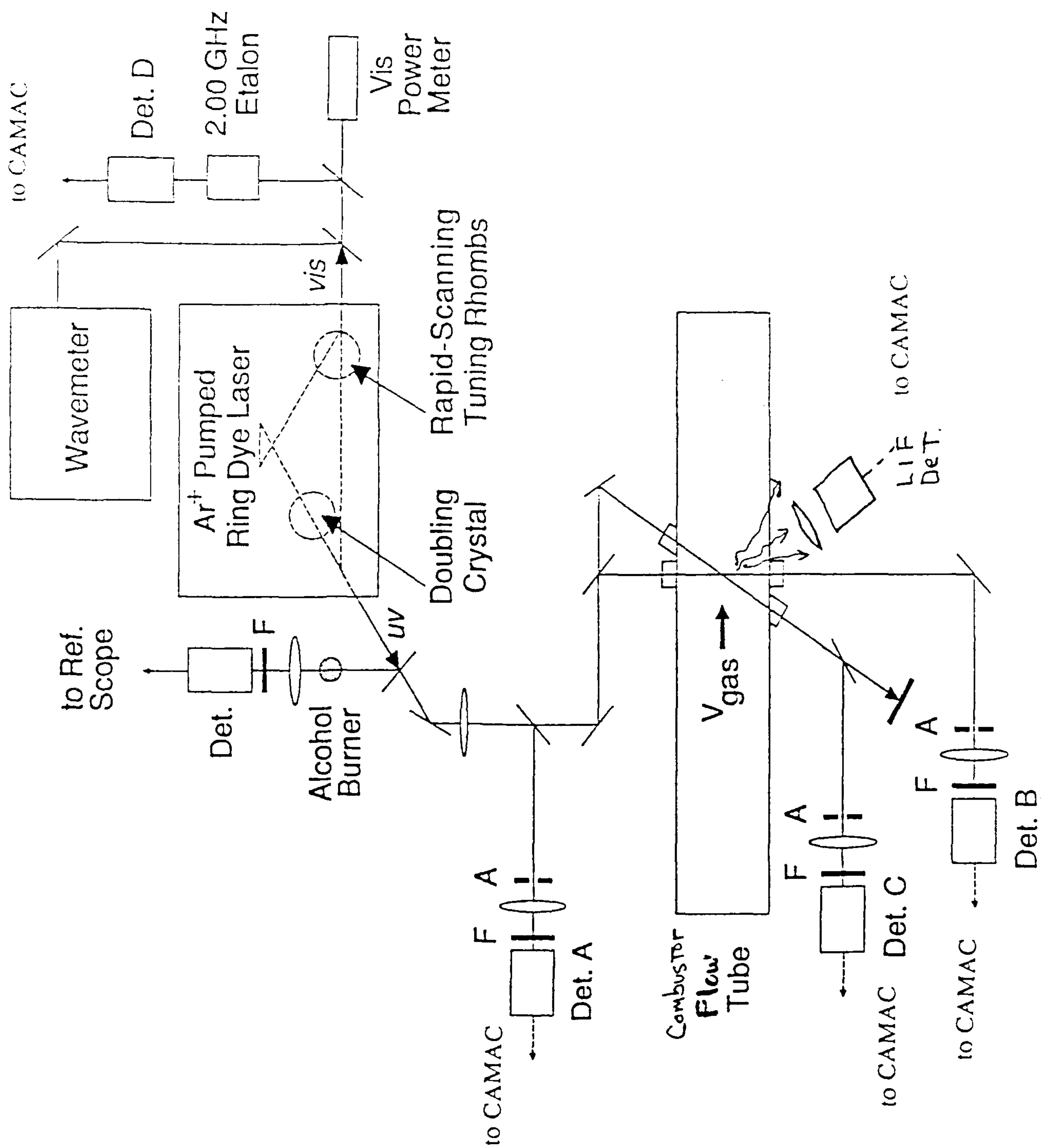

FIGURE 11 Proposed sensor system layout which could be used to record line-of-sight averaged absorption measurements.

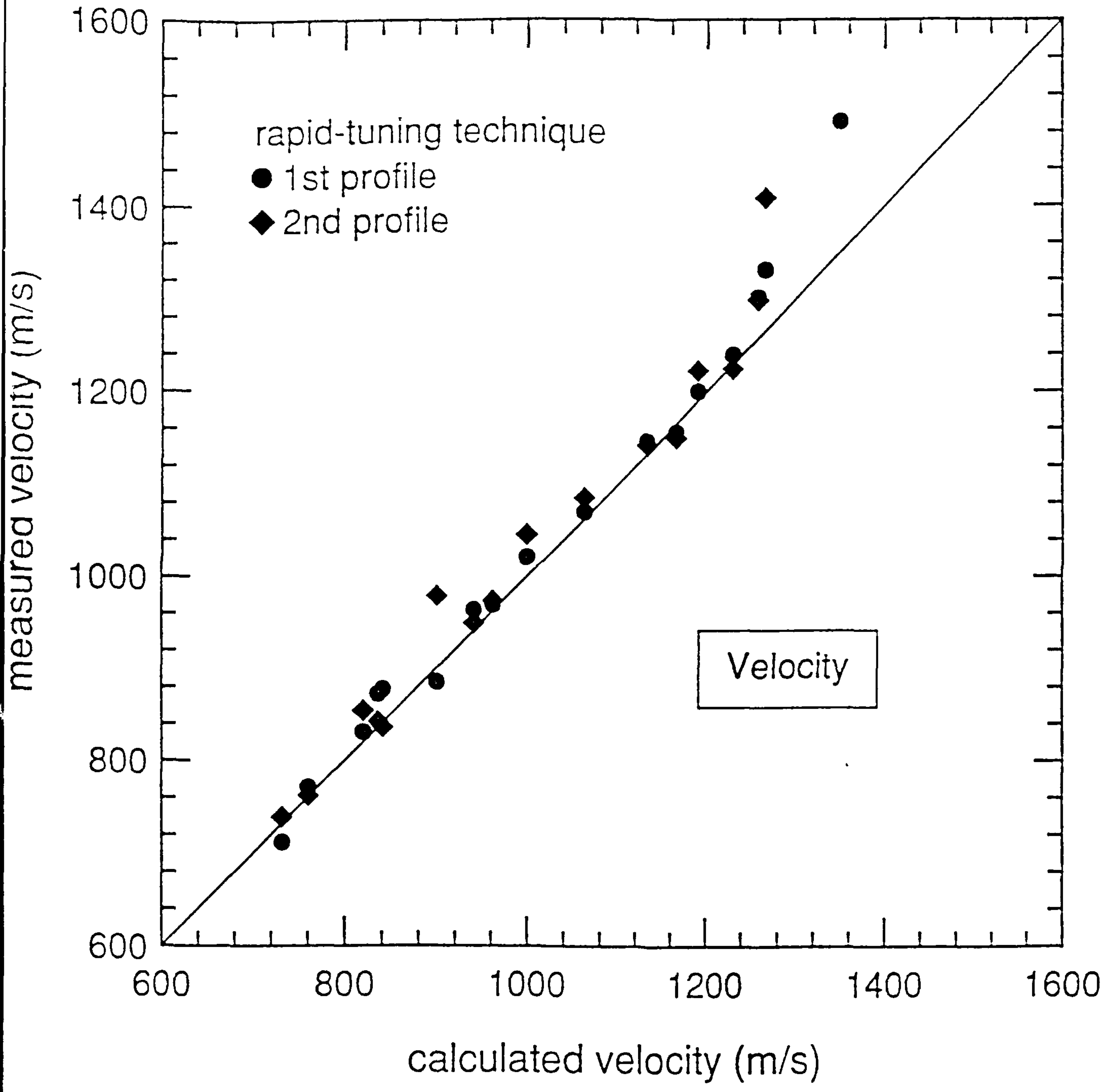

FIGURE 12 Measured line-of-sight gas velocity vs. calculated velocity. Circles and diamonds represent different data. [data from Hanson, et al., to be published]

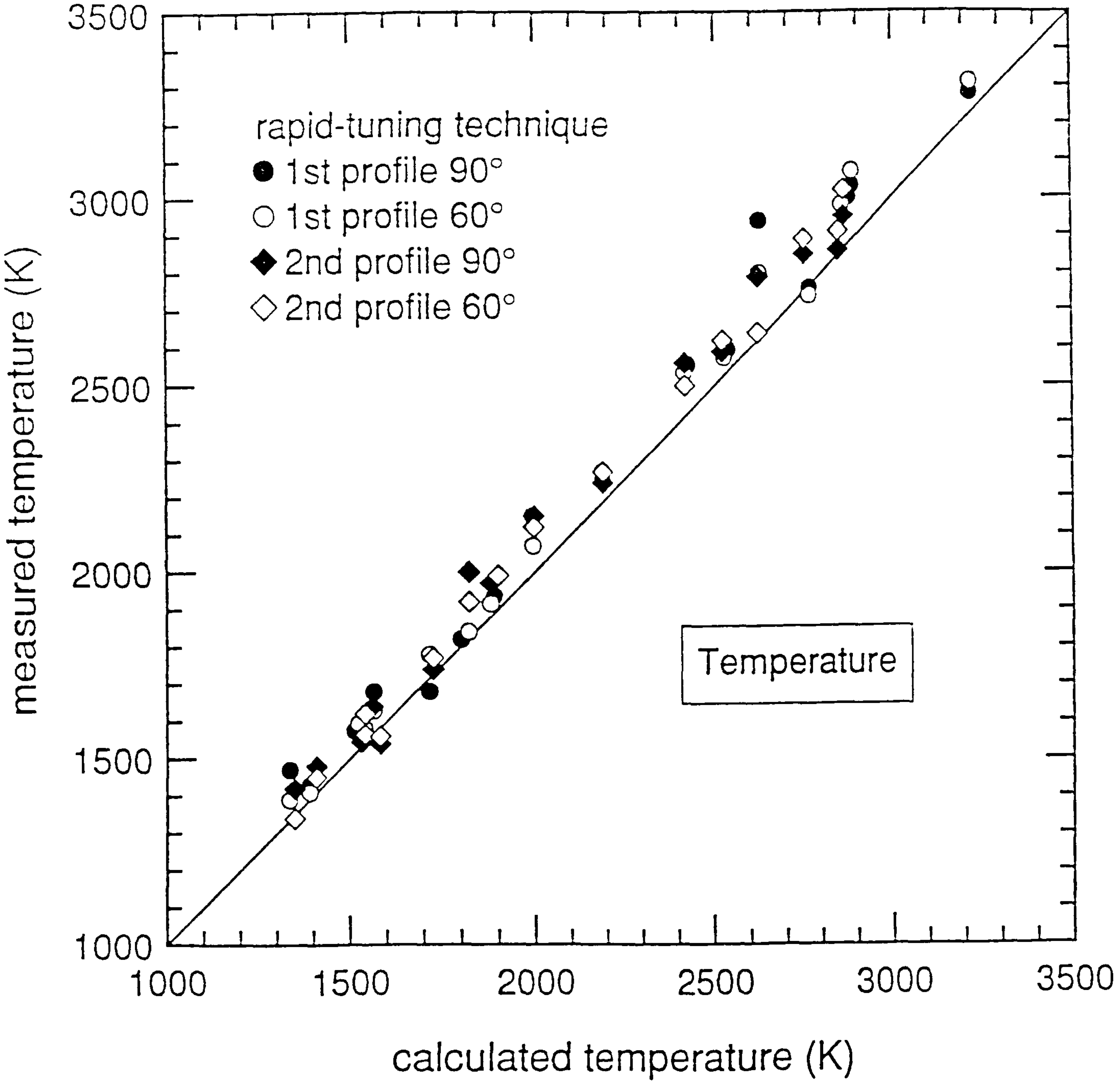

FIGURE 13 Measured line-of-sight gas temperature vs. calculated temperature. [data from Hanson, et al., to be published]

III. PHASE II APPROACH

We propose to develop this approach through refinement of both the hardware and data analysis software. The data system upgrade to the more powerful digitizers will be made first. Following this we need to expand the operator capabilities in viewing and analyzing the data. Rapid scrolling across the data, with fast enlargements will allow the user to select sections of data for analysis. We will incorporate the existing computer models which allow the OH LIF lines to be curve fitted for velocity, temperature, and density determinations. Finally, working with the staff at Wright Laboratory, we will help develop the system to allow mapping of the flow field through translation of the optical system and the handling of such data. We will purchase and modify a ring dye laser for this program and refurbish an Ar+ laser at WL to serve as a pump source. Other laser modifications will be made to simplify the operation of the system.

We propose to develop this prototype in collaboration with Prof. Hanson's group during the first half of the program. During the second half we plan to deliver the prototype to Wright Laboratory and begin tests of the system on the quartz walled combustor being developed there.

CONCLUSIONS

The goal of this Phase I program was to establish the feasibility of using a laser induced fluorescence system to map out the local flow velocity in a supersonic exhaust flow. The system we have demonstrated can accomplish this, as well as the simultaneous measurement of local flow temperature and density. This work required; i) the identification of the species to be studied and the transitions to be used to probe these species; ii) predictions of the densities of these species and the anticipated signal levels which could be attained with commercial laser systems; iii) an experimental demonstration of the approach using a prototype data collection system; and iv) an analysis of the data produced in this demonstration to evaluate signal levels, signal to noise, and the precision of the technique.

All of these goals have been met. Our conclusions are:

1) The species which should be probed to provide information on the exhaust flows is the OH radical.

2) A direct and efficient spectroscopic probe is available for this radical through the A-X transition. We have identified several lines which can be used to probe for both velocity and temperature which offer good sensitivity over a wide range of temperatures.

3) The measurements we have made using our prototype system have demonstrated that this approach is attractive and that the desired information can be easily recovered.

4) We have observed oscillations in the OH concentration as a function of time in a supersonic combustor flow. The oscillations occur with time periods of milliseconds and seem to be the result of uneven mixing in the burner.

5) Several extensions to this approach can be made which will add to the capability of the sensor system. The use of more powerful electronics is one area. The addition of a line-of-sight laser absorption measurement is also attractive for determining mass weighted flow velocity and temperature. The estimated precision and operating range of this proposed sensor are listed on the following page.

SUMMARY OF SYSTEM PERFORMANCE*

I. TIME RESOLVED POINT MEASUREMENTS

Time resolution	$\sim 3\times 10^{-4}$ sec.
Flow velocity range	above 50 m/sec
Flow velocity resolution (for a single system cycle)	$\sim$50 m/sec
Flow temperature resolution (for a single system cycle)	$\sim$5%
Flow local pressure precision	+/- 20%

II. TIME RESOLVED L.O.S. MEASUREMENTS**

Time resolution	$\sim 3\times 10^{-4}$ sec.
Flow velocity range	above 50 m/sec
Flow velocity resolution (for a single system cycle)	$\sim$20 m/sec
Flow temperature resolution (for a single system cycle)	$\sim$2%
Flow pressure (mass wieghted)	2-3%

* Based upon data produced in this study
** Line Of Sight integrated measurements

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